Lethality of Persons due to Debris Throw
Update on Recent Work in Switzerland

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on behalf of Swiss DoD, armasuisse / IOS-SUR - Switzerland

Abstract

Most ammunition safety regulations are still based on quantity-distances (QD), taking into account deterministic criteria like a certain hazardous debris density as decisive and sole measure, but do not focus on the actual hazard to exposed persons. Such regulations often lead to over conservative and costly solutions.

Modern world solutions, however, call for probabilistic risk analysis procedures focussing on the real hazards and allowing to optimise the use of the sparse resources left in our field today, be it money, personnel or space for military activities. On the other hand, innovative probabilistic risk analysis procedures as the one successfully used in Switzerland since the late 70's or the one described in the NATO's AASTP-4 manual also require more sophisticated explosion effect and lethality models than the ones nowadays used in QD-manuals.

This paper describes the new model for calculating the lethality of people staying in the open or in buildings due to explosion produced debris, developed by Bienz, Kummer and Partner Ltd. on behalf of the Swiss DoD during the last years. The model allows taking into account parameters like
- debris number density
- impact angle of debris
- impact energy of debris
- different body positions
- susceptibility of different body parts against debris impact

and for people staying inside buildings
- protection given by building elements
- location of a person inside a room

Further on, an overview on the computer code LambdaT$^©$, used to carry out the necessary calculations, is given. Finally, the results from calculations for a number of structures (mostly brickwork / r.c. structures) exposed to adit and crater debris from explosions in underground installations are shown, and general findings are discussed.

Contents:

1. Background
2. General Calculation of Debris Lethality
3. The Computer Code "LambdaT$^©$"
4. Application and Results
5. Summary

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14. ABSTRACT

Most ammunition safety regulations are still based on quantity-distances (QD), taking into account deterministic criteria like a certain hazardous debris density as decisive and sole measure, but do not focus on the actual hazard to exposed persons. Such regulations often lead to over conservative and costly solutions. Modern world solutions, however, call for probabilistic risk analysis procedures focussing on the real hazards and allowing to optimise the use of the sparse resources left in our field today, be it money, personnel or space for military activities. On the other hand, innovative probabilistic risk analysis procedures as the one successfully used in Switzerland since the late 70's or the one described in the NATO's AASTP-4 manual also require more sophisticated explosion effect and lethality models than the ones nowadays used in QD-manuals. This paper describes the new model for calculating the lethality of people staying in the open or in buildings due to explosion produced debris, developed by Bienz, Kummer and Partner Ltd. on behalf of the Swiss DoD during the last years. The model allows taking into account parameters like - debris number density - impact angle of debris - impact energy of debris - different body positions - susceptibility of different body parts against debris impact and for people staying inside buildings - protection given by building elements - location of a person inside a room Further on, an overview on the computer code LambdaT©, used to carry out the necessary calculations, is given. Finally, the results from calculations for a number of structures (mostly brickwork / r.c. structures) exposed to adit and crater debris from explosions in underground installations are shown, and general findings are discussed.

15. SUBJECT TERMS

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1   Background

Most ammunition safety regulations are still based on quantity-distances (QD), taking into account deterministic criteria like a certain hazardous debris density as decisive and sole measure, but do not focus on the actual hazard to exposed persons. Such regulations often lead to over conservative and costly solutions.

Modern world solutions, however, call for probabilistic risk analysis procedures focussing on the real hazards and allowing to optimise the use of the sparse resources left in our field to-day, be it money, personnel or space for military activities. On the other hand, innovative probabilistic risk analysis procedures as the one successfully used in Switzerland since the late 70's [1 - 3] or the one described in the NATO's AASTP-4 "Manual on Explosives Safety Risk Analysis" [4] also require more sophisticated explosion effect and lethality models than the ones nowadays used in QD-manuals.

This paper describes a new model for calculating the lethality of people staying in the open or in buildings due to debris throw from accidental explosions of ammunition or explosives or due to debris originating from terrorist attacks. This model is currently being developed by Bienz, Kummer & Partner Ltd. on behalf of the Swiss DoD.

2   General Calculation of Debris Lethality

2.1   People Staying in the Open

To calculate the lethality of a person staying in the open due to debris impact, basically the following three elements must be known (Figure 1):

    1) The properties of the incoming debris cloud, per mass class in terms of
- average mass   [kg]
- debris number density   [pieces/m^2]
- velocity   [m/s]
- impact angle   [˚]

    2) The areas of the exposed body parts, distinguished are
- head
- thorax
- abdomen
- limbs

    The respective areas must be known for standing, sitting and lying persons (front and side view), and for men, women and children

3) The basic lethalities

These are the expected partial-lethalities that would result from the impact of a piece of debris with a certain energy on a certain body part.
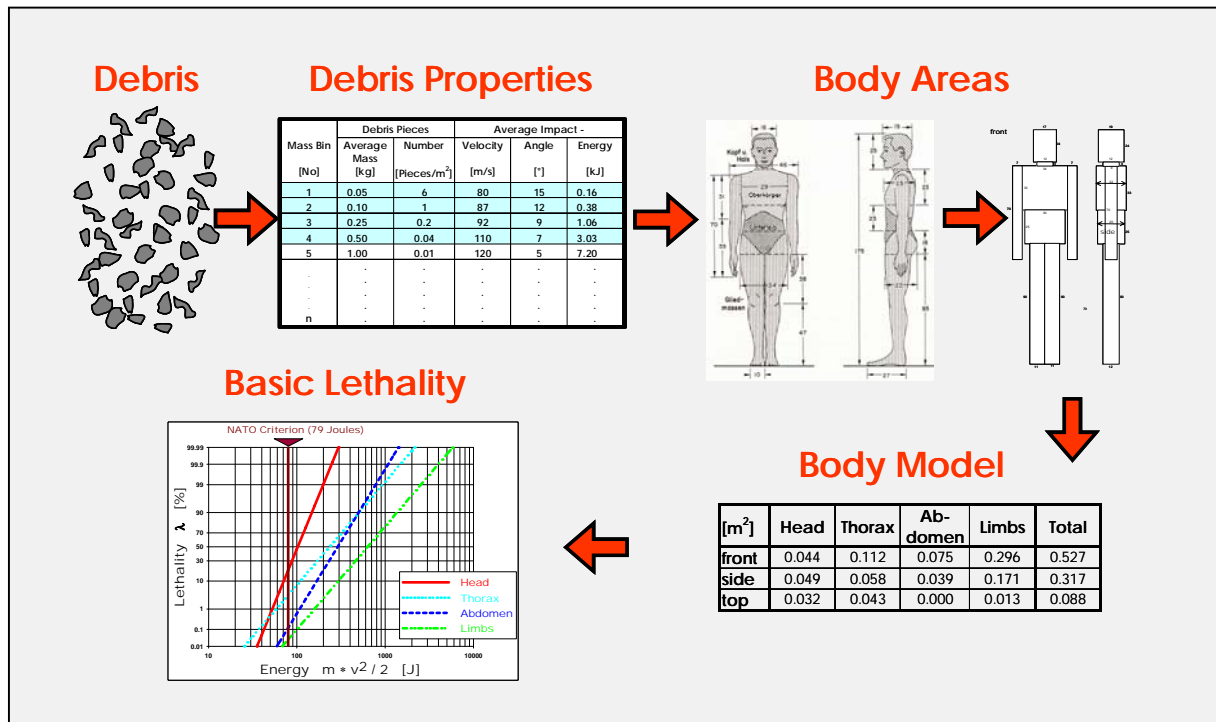

Figure 1: Main Elements for the Calculation of the Debris Lethality of Persons Staying in the Open

A suitable combination of these elements, using respective formulas e.g. for hit probability, finally allows to calculate the lethality of a person being exposed in whatever body position to any kind of debris throw. A possible calculation procedure is given in Figure 2.

The calculation of the lethality of people staying in the open due to debris throw, the related testing that was performed, and all necessary formulas to carry out the analysis are given in detail in Lit. [5].

2.2 People Staying inside Buildings

Basically, the debris lethality of persons staying inside buildings may be calculated with the same procedure as for persons staying in the open. Nevertheless, two major differences exist.

First of all, the properties of the incoming debris cloud will be changed on impact (Figure 3). Depending on the specification of the building material, a piece of debris of a certain mass class with a certain impact energy can be stopped by the building element. If the energy of the impacting piece of debris is high enough, it will perforate the building element, thereby losing some of its energy, and afterwards continue its flight. Furthermore, due to the impact of debris
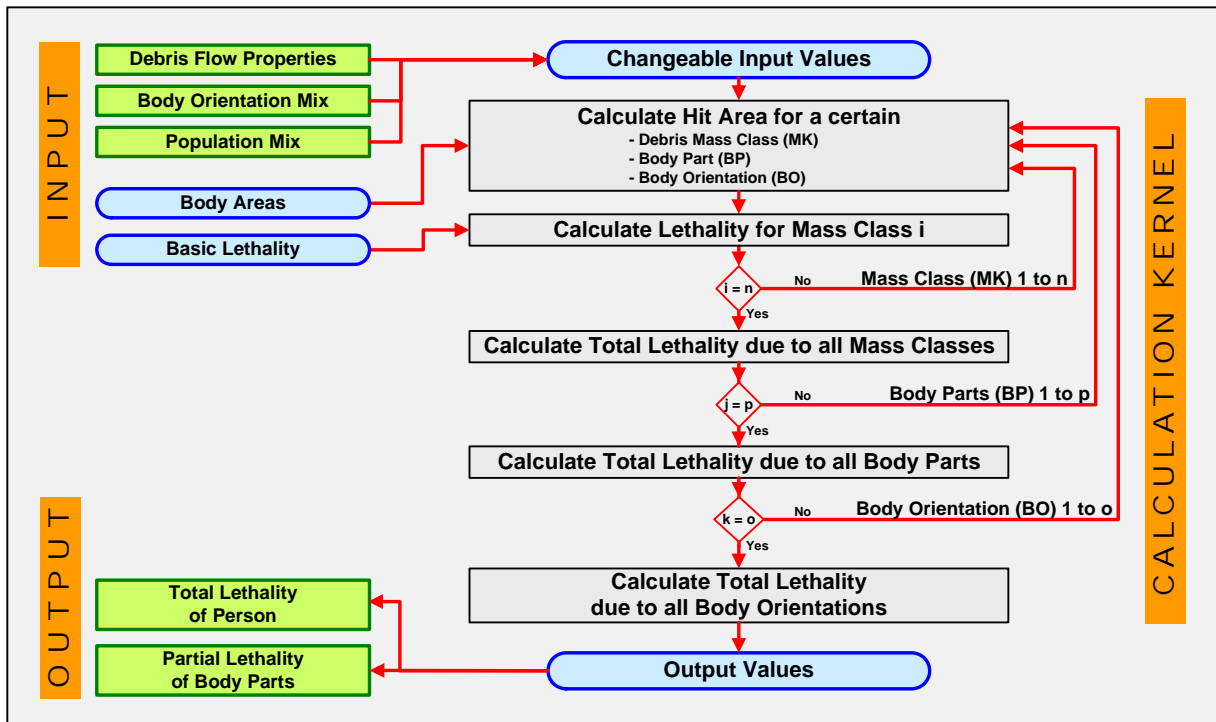
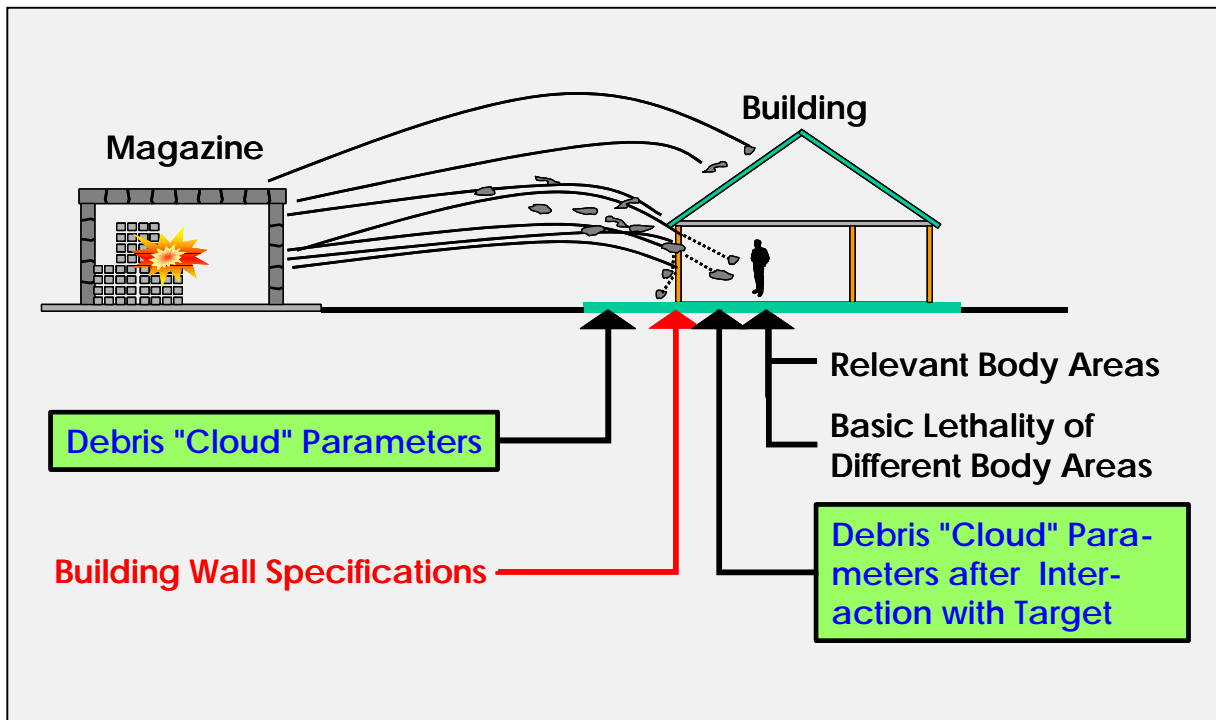*Figure 2: General Calculation Procedure for Persons Staying in the Open*

Figure 3: Influence of Building Elements on Debris Cloud

pieces on a building element, hazardous secondary debris might be generated. This is especially a problem in case of building elements that consist of brickwork.

A lager number of tests have been performed during the last years looking into the building material resistance against debris impact and the danger of secondary building material debris for persons. Results of these tests may be found in Lit. [6, 7].

Secondly, it has to be noted that the lethality of a person subjected to debris throw inside a building room much depends on the following factors (see Figure 4):

1) The impact angle α against the ground of the debris pieces of a certain mass class defines what part of a room will be at least partially protected e.g. by the roof and in what part of the room no protection is given due to window areas.

2) Due to the fact that different areas inside the room get different protection by the building construction, it is important to know where inside the room and in what position an exposed person stays.

3) And finally, it must be known how long a person stays at a certain location in the room. Depending on the usage of the room the duration a person spends at a certain location (in a certain body position) might vary substantially.
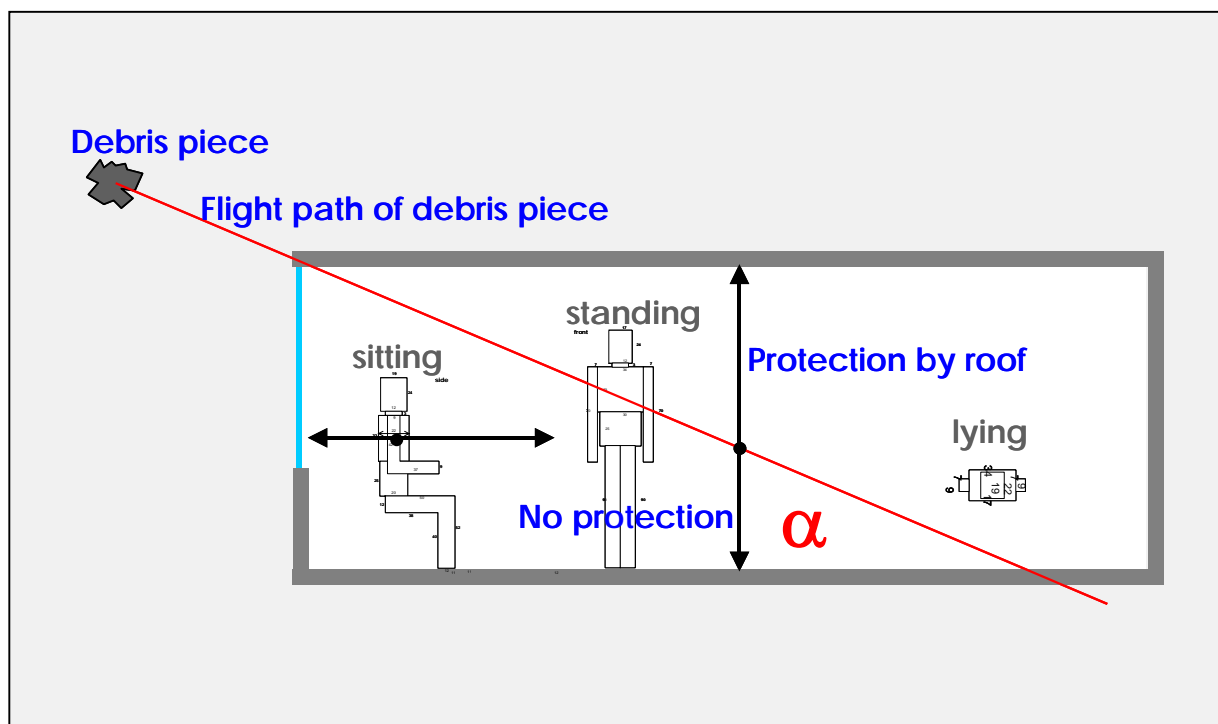

Figure 4:   Connection Between the Debris Flight Path / Impact Angle α and
the Danger for Persons Staying Inside a Room

3 The Computer Code "LambdaT$^©$"

3.1 Requirements

It is obvious that the calculation of debris lethality for persons staying inside buildings is a task involving the combination of many different parameters. Therefore, it was also obvious to develop a corresponding computer program.

The task was to develop an easy to use, fast running software at little costs that would allow to calculate lethalities in rooms of a building and to document the result. The following parameters should be easily changeable:

1) Debris cloud data (density, mass, velocity, impact angle)
2) Building construction (dimensions of rooms, wall/roof material, thickness, impact resistance)
3) Exposure of persons in the rooms (location, body position, duration of stay)

Further, the code should be flexible to allow doing the necessary calculations for all the building types we had in mind (excluding high-rise buildings).

As the budget for developing the code was too limited - as always - not all initially planned features could be implemented and certain short cuts had to be made (see Chapter 3.3). LambdaT$^©$ was developed using Microsoft VisualBasic 6 and Microsoft Access 2000 for the Microsoft XP platform [8].

3.2 How LambdaT$^©$ works

LambdaT$^©$ is designed to handle a generic building structure consisting of two floors and four rooms, as shown in Figure 5. Structures with more storeys or more rooms can easily be approximated with a limited loss of accuracy, however.

Each room contains 40 Lethality Calculation Points (LCP). Horizontally they are spaced evenly in 10 rows, vertically four layers represent certain body parts, as shown in Figure 6. Basically, LambdaT$^©$ now calculates for each debris mass class and all 40 LCP all partial-lethalities as discussed in 2.1. At each LCP the possible protection by building elements is taken into account. The results are stored in a matrix and later on combined with the stored exposure data. A general flow-chart of the code is given in Figure 7.

Figure 8 shows the main user interface (GUI). It consists of an input section and an output/result section.

The input section contains sub-windows for the input of debris data, building data and exposure data. In addition, it allows loading and saving of the input data. Furthermore, the sub-window for exposure data contains pre-defined values for body positions and duration of stay
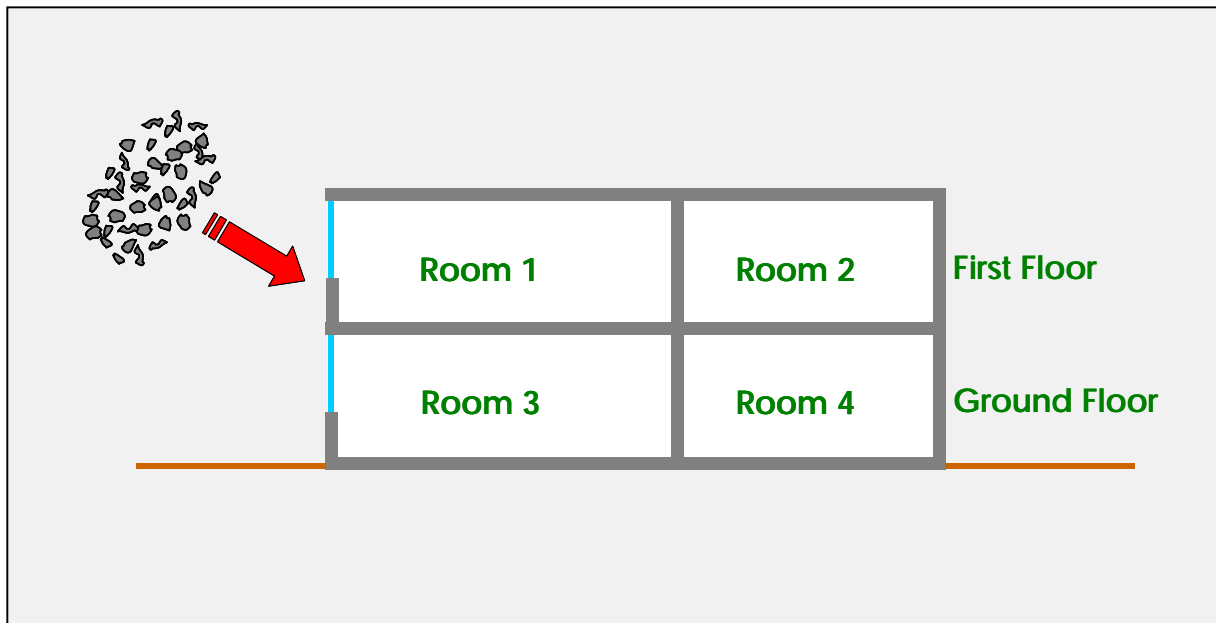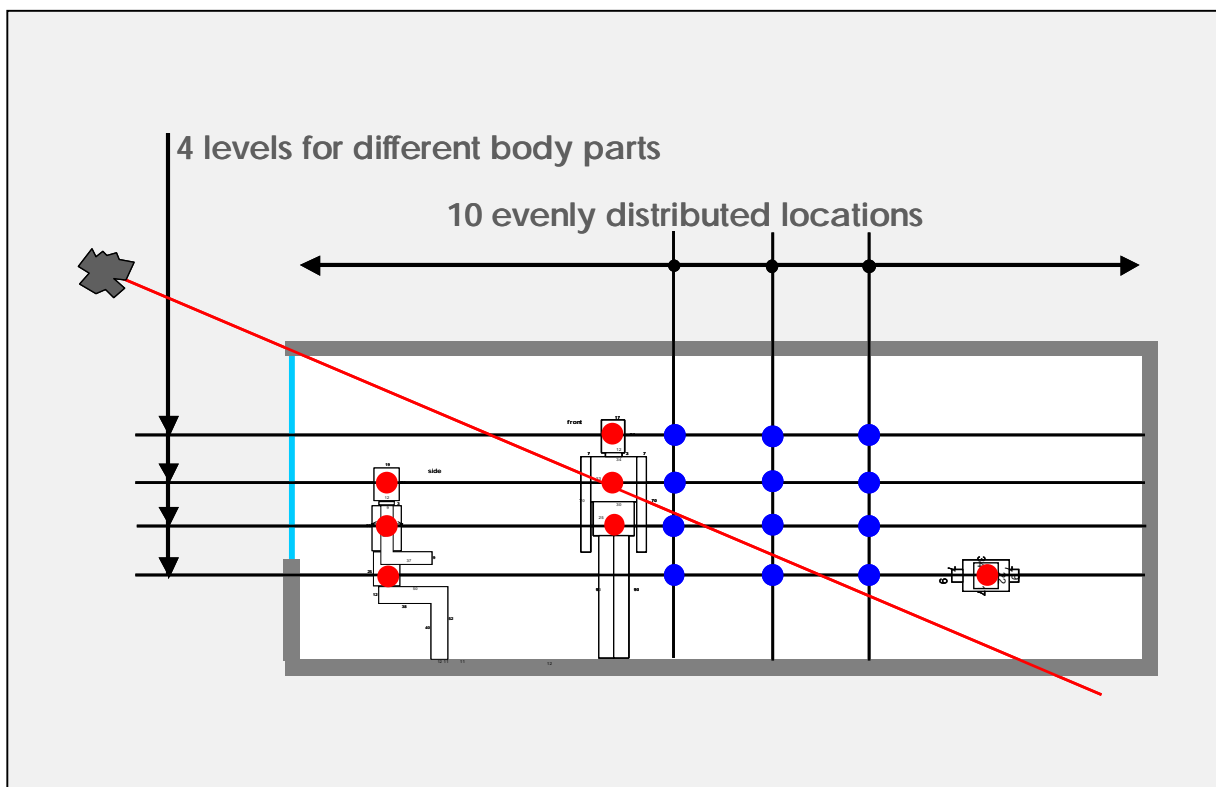
Figure 5: Generic Building Structure

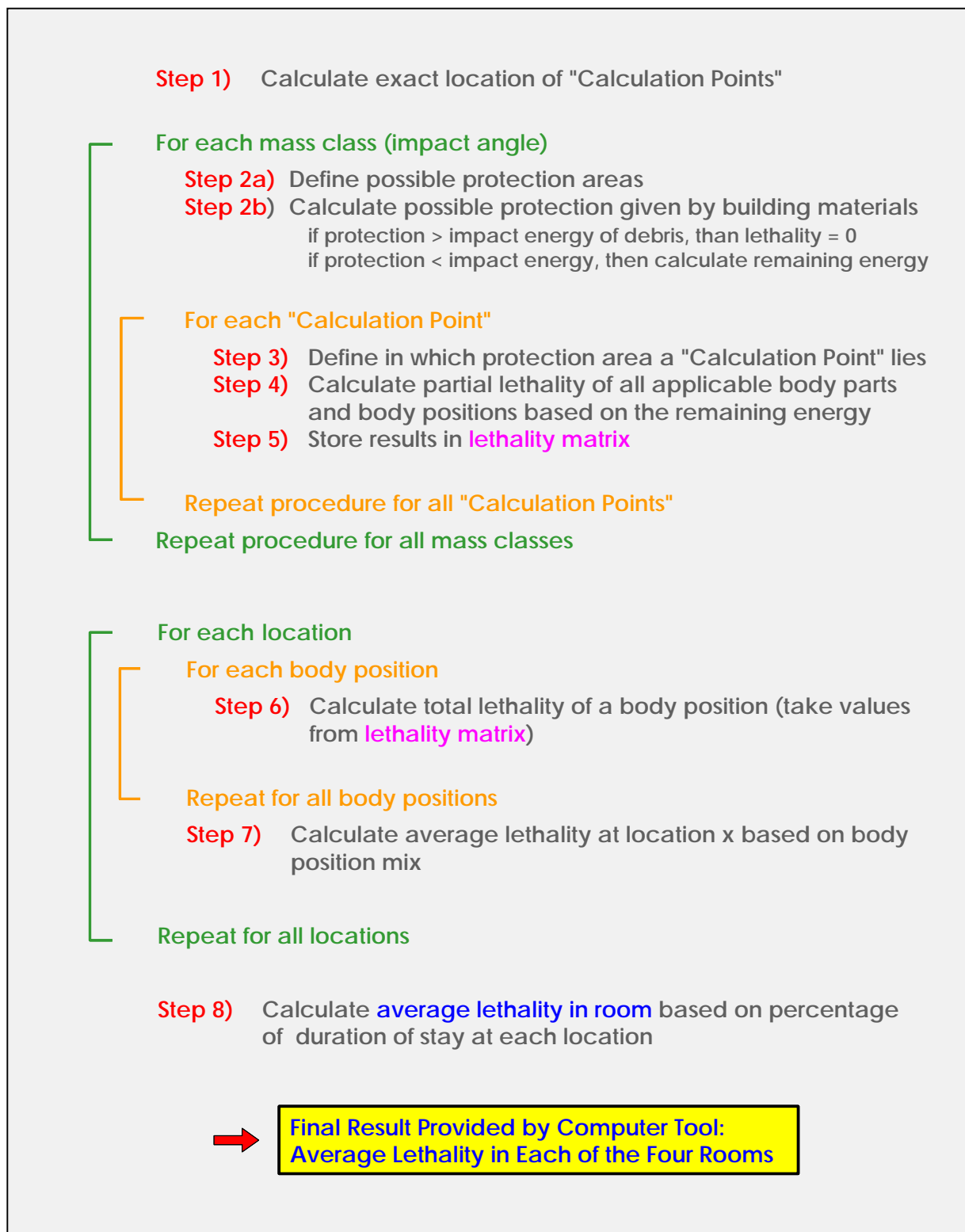*Figure 6: Location of the Lethality Calculation Points (LCP, blue)*

Step 1)   Calculate exact location of "Calculation Points"

For each mass class (impact angle)

  Step 2a) Define possible protection areas
  Step 2b) Calculate possible protection given by building materials
        if protection > impact energy of debris, than lethality = 0
        if protection < impact energy, then calculate remaining energy

  For each "Calculation Point"

    Step 3) Define in which protection area a "Calculation Point" lies
    Step 4) Calculate partial lethality of all applicable body parts
         and body positions based on the remaining energy
    Step 5) Store results in lethality matrix

  Repeat procedure for all "Calculation Points"
Repeat procedure for all mass classes

For each location

  For each body position

    Step 6) Calculate total lethality of a body position (take values
         from lethality matrix)

  Repeat for all body positions
    Step 7) Calculate average lethality at location x based on body
         position mix

Repeat for all locations

Step 8)   Calculate average lethality in room based on percentage
       of duration of stay at each location

Final Result Provided by Computer Tool:
Average Lethality in Each of the Four Rooms
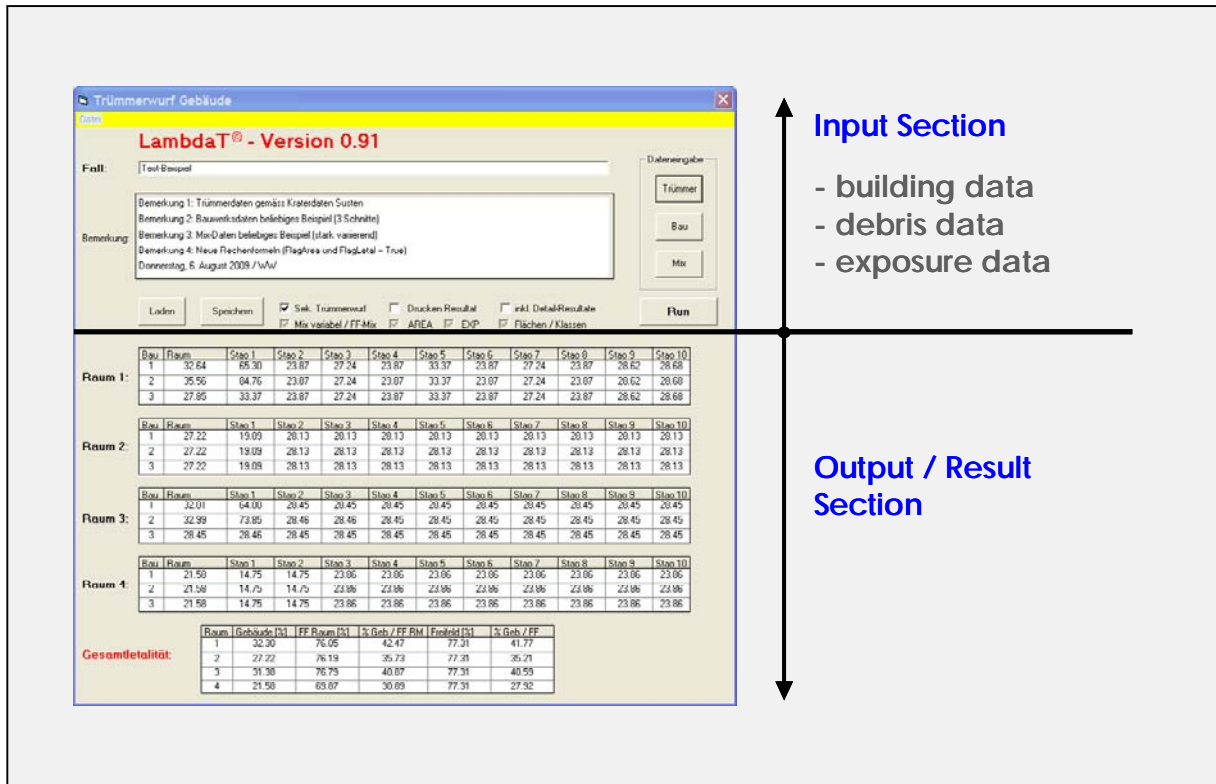
Figure 7:   General Calculation Procedure

Figure 8: Main User Interface of LambdaT©

at a certain location in the room for a number of typical rooms of a house, like kitchen, living room, sleeping room, office, etc.

The result section (Figure 9) shows for each room the average lethality at each location for the pre-defined exposure data. Below, the average lethality in each room for the chosen exposure is given, allowing to easy calculate the average lethality in the whole building. Further on, for comparison the lethality for free field exposure at the same distance from the PES as the room/building is also displayed. This shows at one glance the overall protection against debris throw provided by the building construction.

3.3 Short Cuts

As mentioned above certain simplifications had to be made in this version of LambdaT© due to budget restrictions. The most important ones are:

- Window areas (glass) are treated as open areas. This implies the assumption that a window/glass pane does not give any protection against impacting debris pieces. In many cases, however, it can be assumed that the glass pane is already destroyed by the air blast overpressure when the debris arrives.
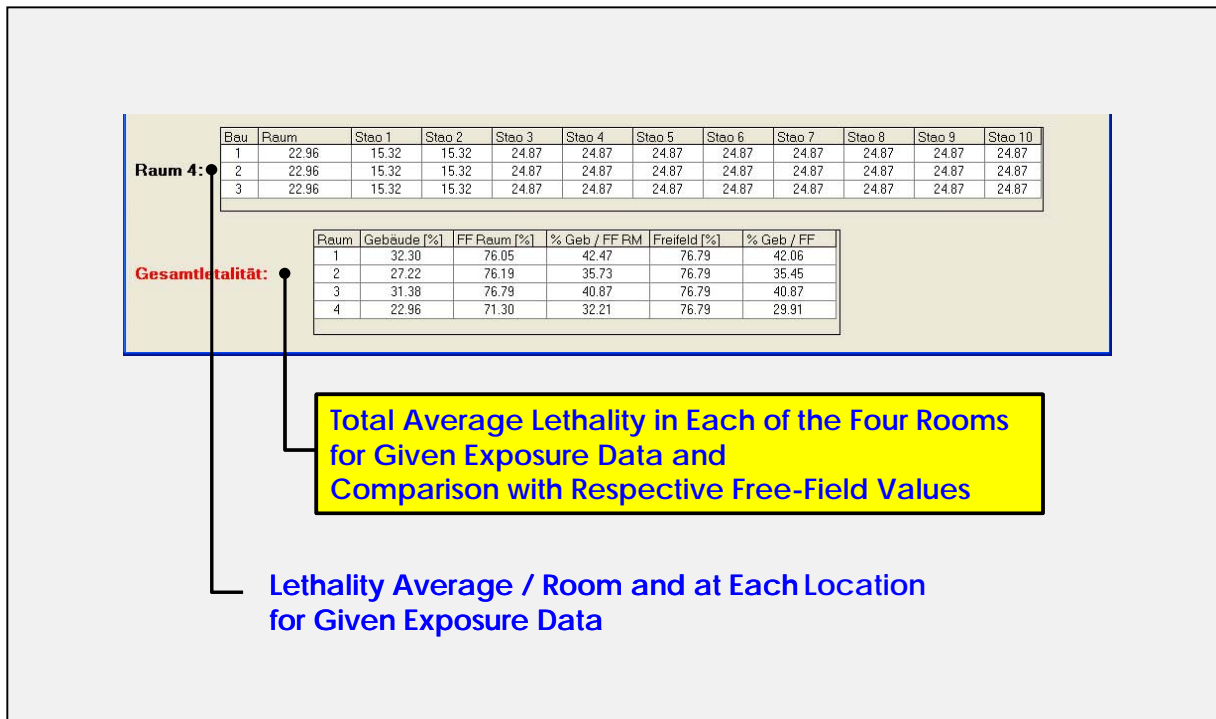
Figure 9:   Result Section of LambdaT©

- It is not possible to take into account interior doors. Therefore, it is assumed that all interior walls are without doors.

- It is assumed that the flight path (angle α against the ground) of incoming debris pieces does not change upon impact and perforation of a building element.

- Likewise, it is assumed that the mass of an impacting and perforating piece of debris will not be reduced during the perforation process.

- The influence of secondary debris pieces on the lethality of persons inside a building room is treated in a simplified way.

4   Application and Results

4.1   General Procedure

After an intensive testing of LambdaT© in the beginning of this year, it was decided to use the software for developing new formulas and diagrams for lethality as a function of debris density for debris throw from craters and adit tunnels of underground ammunition storage installations.

In a first phase four different types of buildings were chosen (taken from AASTP-4 [4]). All buildings are either residential buildings or office blocks and are made solely of reinforced concrete and brickwork (Figure 10). The reason for this selection was the availability of the perforation resistance of the construction materials used in these buildings. For other building materials like wood, sheet steel, etc. perforation tests are still pending.

Figure 10: Building Types Investigated in Phase 1

After that, each of the real buildings had to be transformed into a manageable model. This was done by developing a simplified ground plan for each storey of each building type (Figure 11), including the specification of the materials used and the thickness of each building element. In addition the use of each room had to be defined and the respective exposure of persons had to be assigned.

In the next step LambdaT$^{©}$ was used to calculate the lethalities as a function of the debris density, assuming that a building can be hit by debris throw from all 4 sides (front, back, both sides). Depending on the materials used for the building elements, the size of the window area and the exposure of persons in the different rooms, the resulting lethality will be different.

4.2   Results

Figure 12 shows the result of the calculations for all 4 building types for debris throw originating from the adit of underground ammunition storage installations. As can be seen, for this
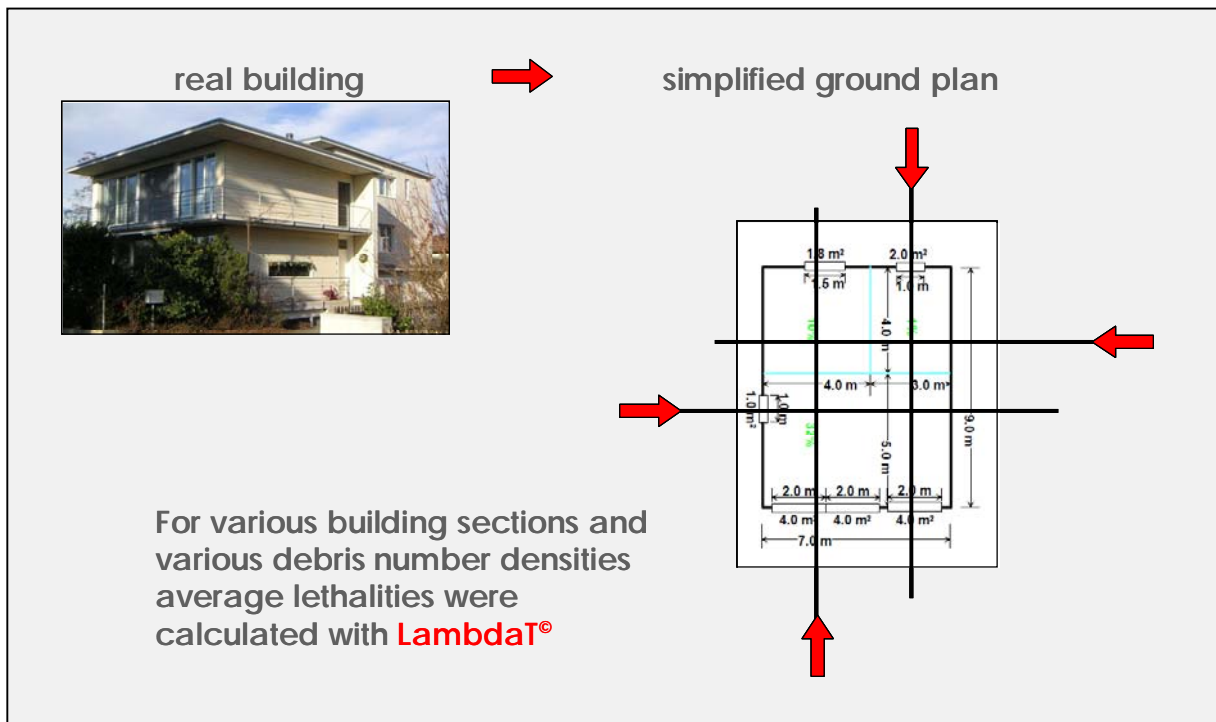
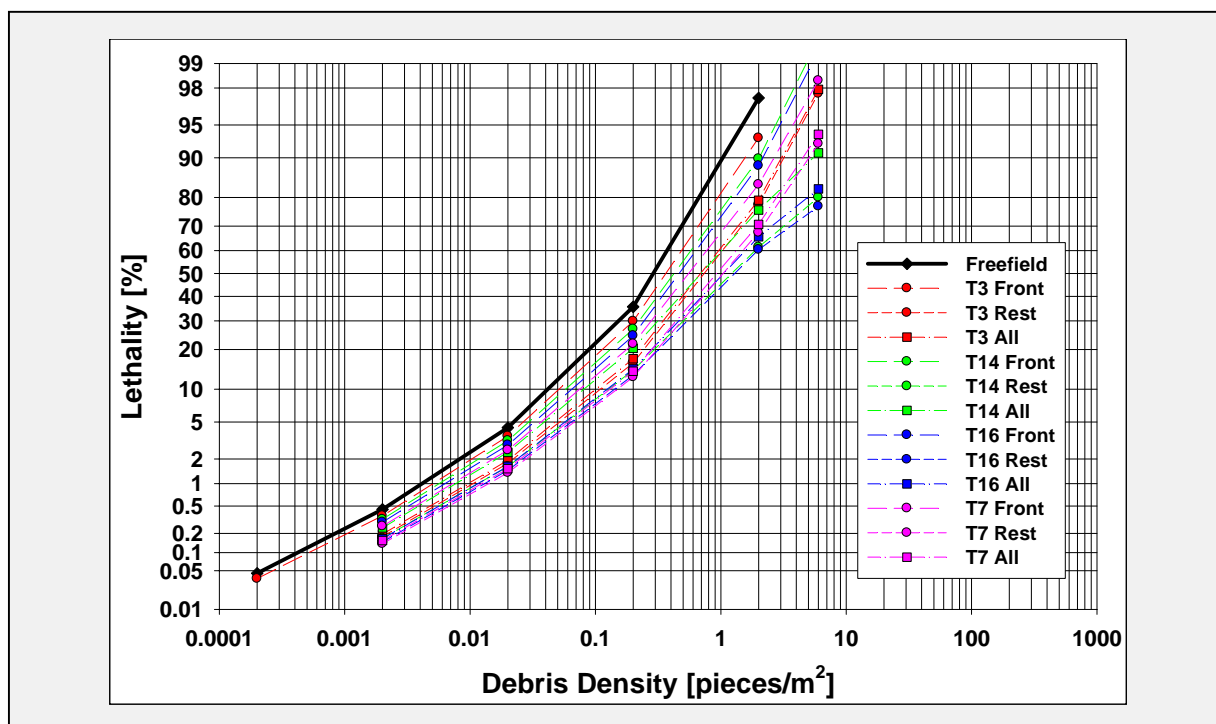*Figure 11: From the Real Building to a Manageable Model*

Figure 12:   Lethality due to Adit Debris Throw for Various Cross-Sections and Combinations Thereof Through the Investigated four Building Types

type of explosion effect and these types of buildings the calculated lethality curves lie relatively close together. However, the calculations also showed that the window area is an important parameter.

Nevertheless, taking into account the overall variation in building constructions, usage of buildings etc., it obviously does not make sense to distinguish between so many curves with so little difference. Therefore, the next logical step was to simplify the procedure to make it user-friendly. The 12 curves in Figure 12 were reduced to three representative curves and a table assigning the different building types to one of the representative curves, taking into account their orientation towards the PES and the window area.

The final result is shown in the following three figures. Figure 13 shows the representative lethality curves for debris throw originating from adits of underground storage installations. The horizontal axis shows the number density of debris pieces - with a mass of at least 150 g - per m^2. The vertical axis shows the respective average lethality of persons staying inside buildings or in the open (free-field).

Figure 14 shows the same result for debris originating from craters of underground storage installations. As can be seen, there is a remarkable difference between adit and crater debris throw for the buildings investigated so far. This is manly attributed to the different impact angles of adit and crater debris.

Finally, Figure 15 gives the connection between the different building types, the window (glass) area and the building orientation with the respective lethality curves in Figure 13 and 14.
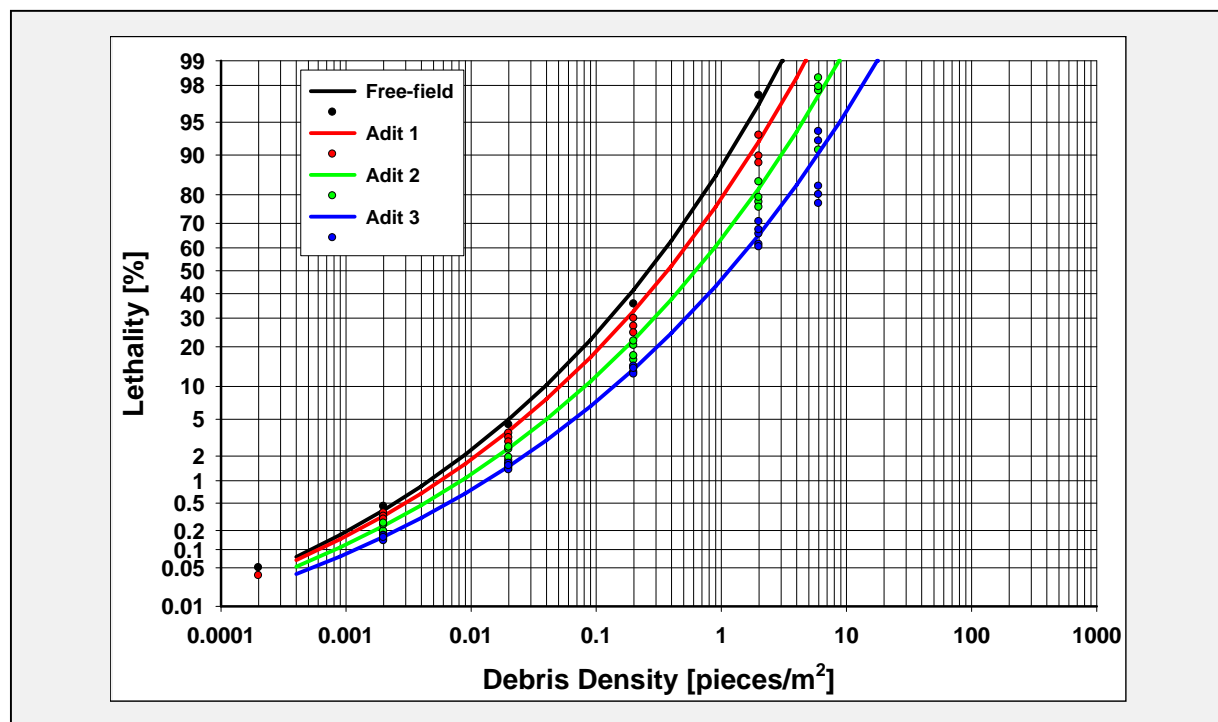

Figure 13: Final Lethality Curves for Adit Debris Throw from Underground Installations
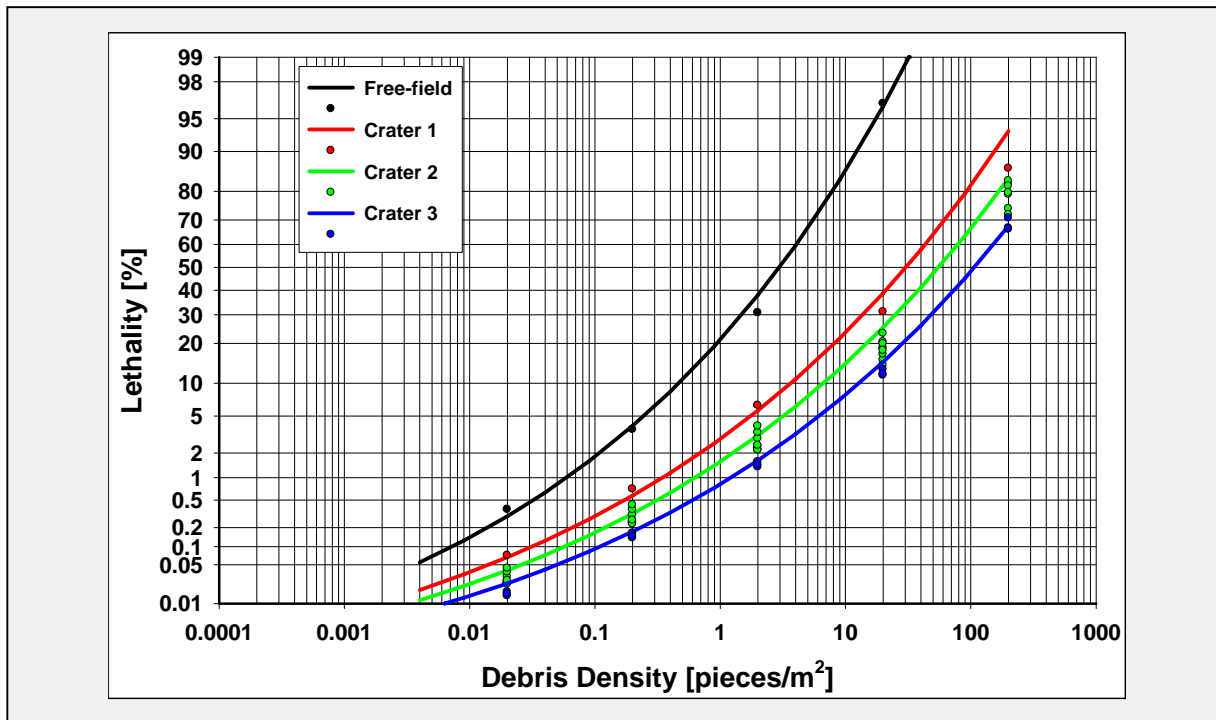
Figure 14: Final Lethality Curves for Crater Debris Throw from Underground Installations

Building-Type		Windows Area, Orientation	Adit Debris Throw			Crater Debris Throw		
No.	Code		A1	A2	A3	C1	C2	C3
3	EFF-2G	1)		X			X	
		2)	X			X		
		3)		X			X	
7	MFF-3G	1)			X		X	
		2)		X			X	
		3)			X		X	
14	IHF-1G	1)		X				X
		2)	X				X	
		3)			X			X
16	BUF-3G	1)			X			X
		2)	X				X	
		3)			X			X

1)	All facades: window width < 50% of facade width
2)	At least one facade with ≥ 50% window width (and h window > 0.5m) and a facade ≥ 50% window width facing the PES
3)	At least one facade with ≥ 50% window width and a facade < 50% window width facing the PES

Figure 15: Connection Between Building Types, Window Area and Building Orientation with the Representative Lethality Curves

5   Summary

In this paper it is shown how the lethality of persons exposed to debris throw - inside and outside buildings - can be calculated.

Basically, the procedure presented and the related software LambdaT$^©$ can be used to calculate the lethality of persons staying in any type of building that is subjected to any type of debris throw, be it from accidental explosions during storage and transport of ammunition as well as debris throw originating from terrorist attacks.

The procedure can be adapted to new knowledge, be it concerning the basic lethalities or the behaviour of building materials under debris impact, and changes may be implemented easily into the software. Further, given the respective data for building material perforation and the basic lethalities, the procedure may well be used also for calculating lethalities due to primary fragments.

And last but not least, this procedure is a major step forward in view of a more realistic assessment of the hazards from debris throw from explosions of ammunition or explosives compared to only applying the 79 J criteria.

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LamdaT©, Version 0.9 - Kurzbeschreibung und durchgeführte Tests
Generalsekretariat VBS - IOS / SUR
Bienz, Kummer & Partner AG
Kummer, Peter; Nussbaumer, Peter; Willi, Walter
TM 150-37 / 16.12.2009

Lethality of Persons due to Debris Throw

## Update on Recent Work in Switzerland

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1. General Calculation Procedure
2. Persons Staying in Buildings
3. Software LambdaT$^{©}$
4. Application
5. Summary

Bienz, Kummer & Partner Ltd. - Switzerland

1. General Calculation Procedure (1)

• **Overview (persons in free-field)**

Debris
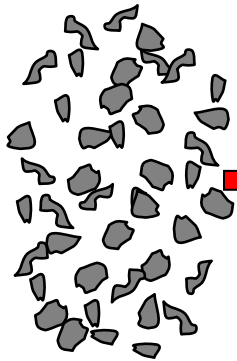
Debris Properties

Mass Bin	Debris Pieces		Average Impact -		
	Average Mass	Number	Velocity	Angle	Energy
[No]	[kg]	[Pieces/m²]	[m/s]	[°]	[kJ]
1	0.05	6	80	15	0.16
2	0.10	1	87	12	0.38
3	0.25	0.2	92	9	1.06
4	0.50	0.04	110	7	3.03
5	1.00	0.01	120	5	7.20
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
n	.	.	.	.	.

Body Areas
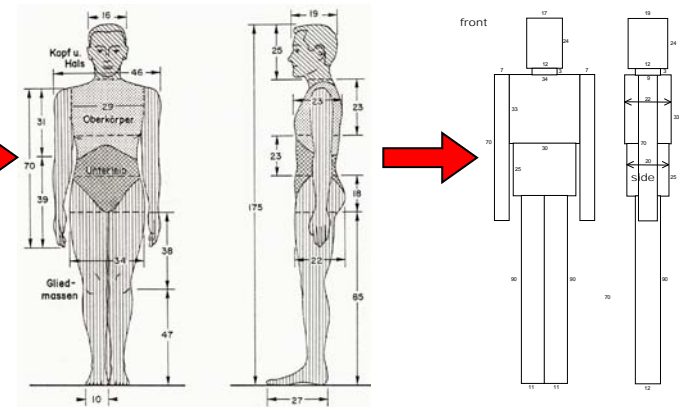
Body Model

[m²]	Head	Thorax	Ab-domen	Limbs	Total
front	0.044	0.112	0.075	0.296	0.527
side	0.049	0.058	0.039	0.171	0.317
top	0.032	0.043	0.000	0.013	0.088

Basic Lethality

NATO Criterion (79 Joules)

Lethality λ [%]

Energy m * v² / 2 [J]

Head
Thorax
Abdomen
Limbs

1. General Calculation Procedure (2)

- ## Calculation Flow Chart (persons in free-field)

INPUT

- Debris Flow Properties
- Body Orientation Mix
- Population Mix
- Body Areas
- Basic Lethality

OUTPUT

- Total Lethality of Person
- Partial Lethality of Body Parts

CALCULATION KERNEL

Changeable Input Values

Calculate Hit Area for a certain
- Debris Mass Class (MK)
- Body Part (BP)
- Body Orientation (BO)

Calculate Lethality for Mass Class i

i = n — No — Mass Class (MK) 1 to n
Yes

Calculate Total Lethality due to all Mass Classes

j = p — No — Body Parts (BP) 1 to p
Yes

Calculate Total Lethality due to all Body Parts

k = o — No — Body Orientation (BO) 1 to o
Yes

Calculate Total Lethality due to all Body Orientations

Output Values

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2. Persons Staying in Buildings (1)

- **Lethality in Free-Field versus Lethality in Buildings**

➡️ **Protection given by building elements**
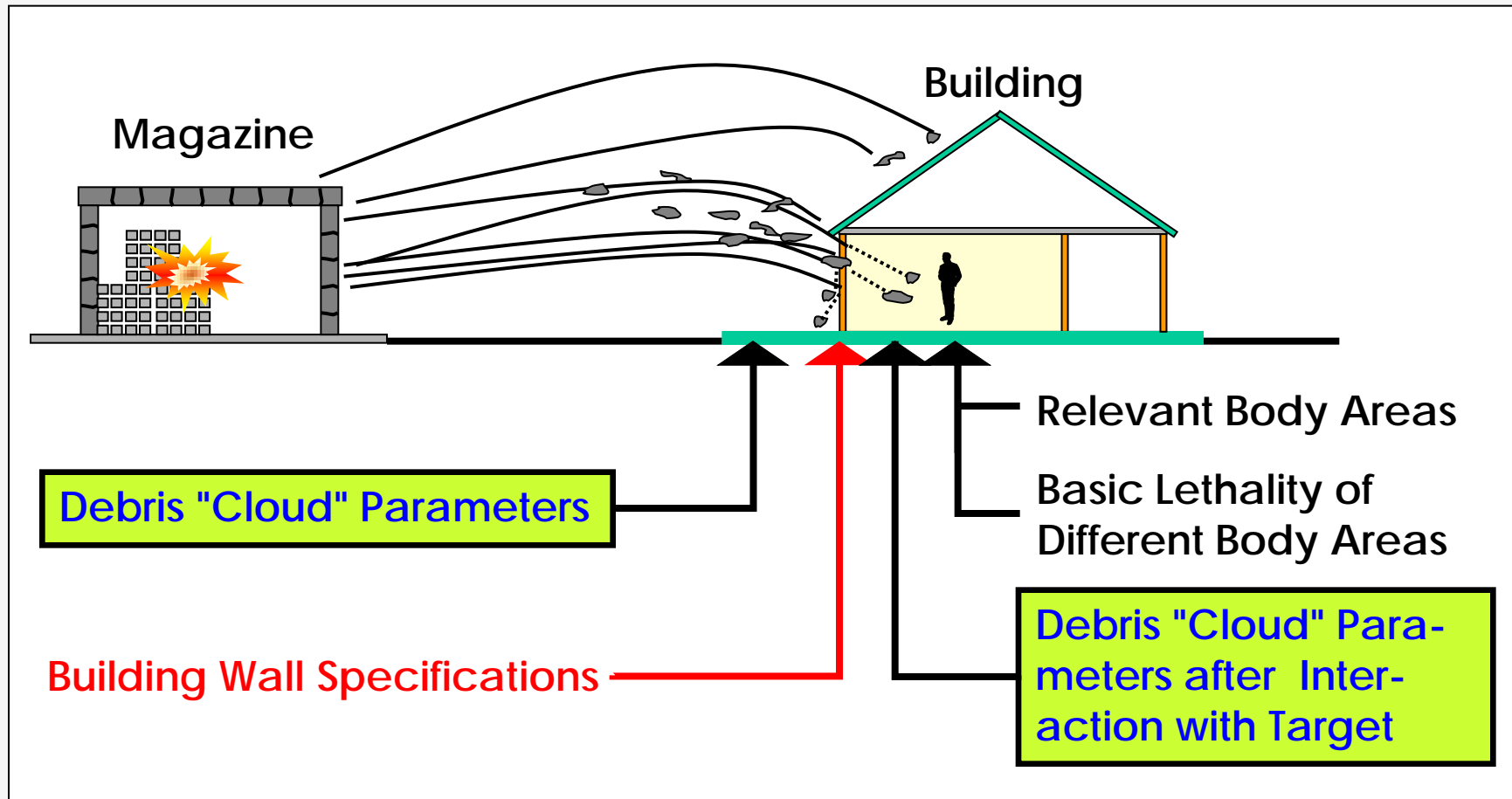
2. Persons Staying in Buildings (2)

- ## Dependence of Lethality on
  - Location of person in room
  - Duration of stay at a room location
  - Body position (sitting, standing, …)
  - Impact angle of debris piece α

➡️ **Protected Area Varies with Debris Mass Class / Impact Angle**

Debris piece

Flight path of debris piece

standing

sitting

Protection by roof

lying

No protection

α
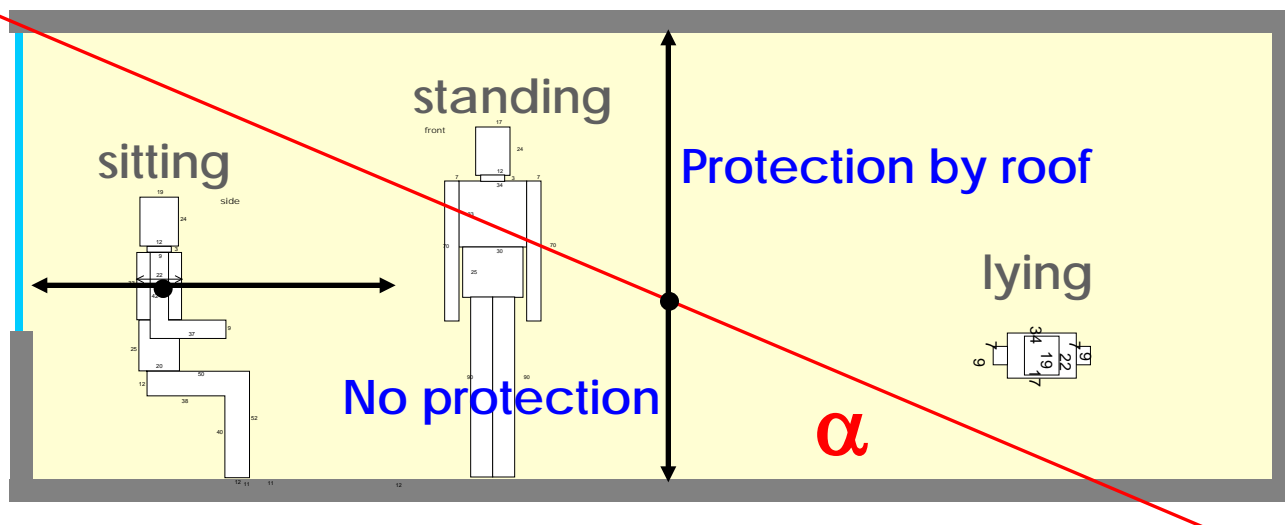
3. Software LambdaT© (1)

- ## Basic House / Room Structure (section)

  - ### Main input parameters for each room

    - Room dimensions
    - Wall and roof specifications
    - Window area
    - Exposure data

Room 1   Room 2   **First Floor**

Room 3   Room 4   **Ground Floor**
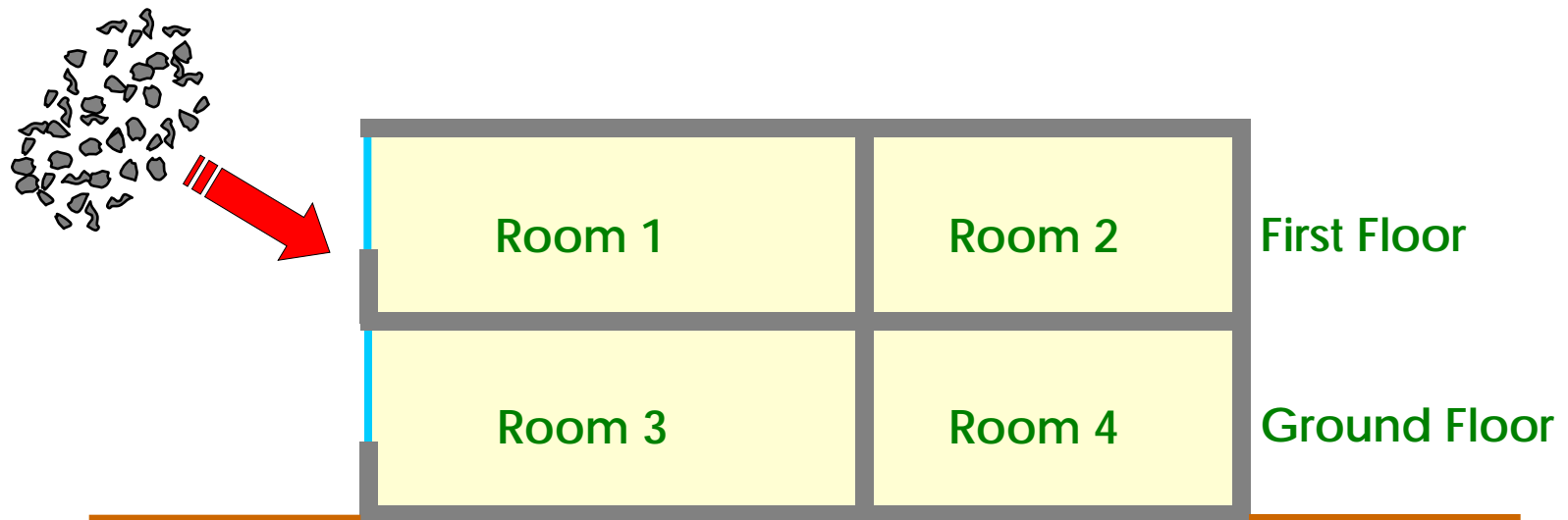
3. Software LambdaT© (2)

- **Lethality Calculation Points (40 LCP, blue)**

4 levels for different body parts

10 evenly distributed locations
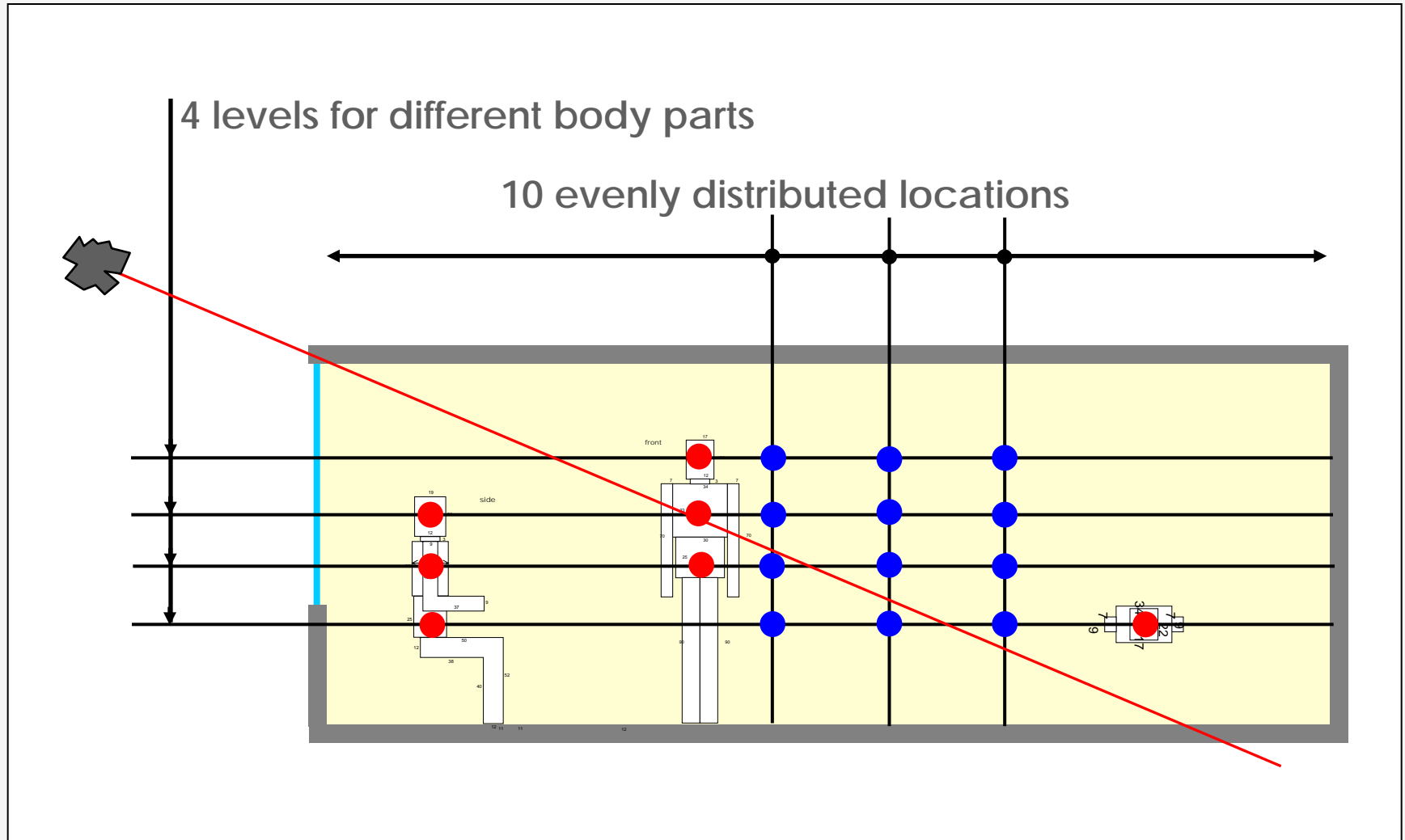
3. Software LambdaT© (3)

- ## GUI - Main Input and Result Screen

Input Section

- building data
- debris data
- exposure data

Output / Result Section

3. Software LambdaT$^©$ (4)

- **GUI - Result Screen Details**

Raum 4:

Bau	Raum	Stao 1	Stao 2	Stao 3	Stao 4	Stao 5	Stao 6	Stao 7	Stao 8	Stao 9	Stao 10
1	22.96	15.32	15.32	24.87	24.87	24.87	24.87	24.87	24.87	24.87	24.87
2	22.96	15.32	15.32	24.87	24.87	24.87	24.87	24.87	24.87	24.87	24.87
3	22.96	15.32	15.32	24.87	24.87	24.87	24.87	24.87	24.87	24.87	24.87

Gesamtletalität:

Raum	Gebäude [%]	FF Raum [%]	% Geb / FF RM	Freifeld [%]	% Geb / FF
1	32.30	76.05	42.47	76.79	42.06
2	27.22	76.19	35.73	76.79	35.45
3	31.38	76.79	40.87	76.79	40.87
4	22.96	71.30	32.21	76.79	29.91

Total Average Lethality in Each of the Four Rooms for Given Exposure Data and Comparison with Respective Free-Field Values

Lethality Average / Room and at Each Position for Given Exposure Data

3. Software LambdaT© (5)

- **Short Cuts**

    - Window areas are treated as open areas (glass assumed to be already broken by air blast when debris arrive at target)

    - Not possible to take into account doors in interior walls

    - Assumed that the flight path (angle α against the ground) of the debris pieces does not change upon perforation of a building element

    - Assumed that the mass of the debris pieces does not change when perforating a building element

    - Secondary debris throw taken into account with a simplified procedure (reduced energy reduction)

    ➡ Most of the short cuts are conservative approaches

4. Application (1)

- **Building Types Investigated**

    - **Common characteristics**

        - Either residential building or office block
        - Walls made of clay bricks or reinforced concrete
        - Floors made of reinforced concrete
        - Roof / roof slab made of reinforced concrete

    - **Reason for selection**

        - Perforation resistance of construction materials known

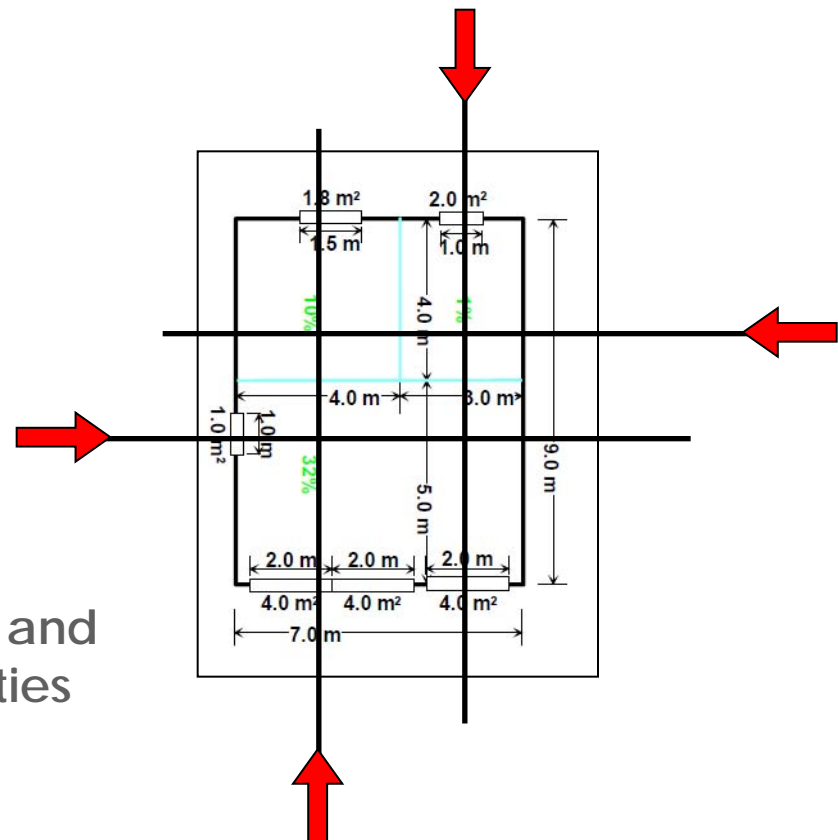| 3 - EFF-2G	7-MFF-3G	14 - IHF-1G	16 - BUF-3G

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4. Application (2)

- ## From the Real Building to a Manageable Model
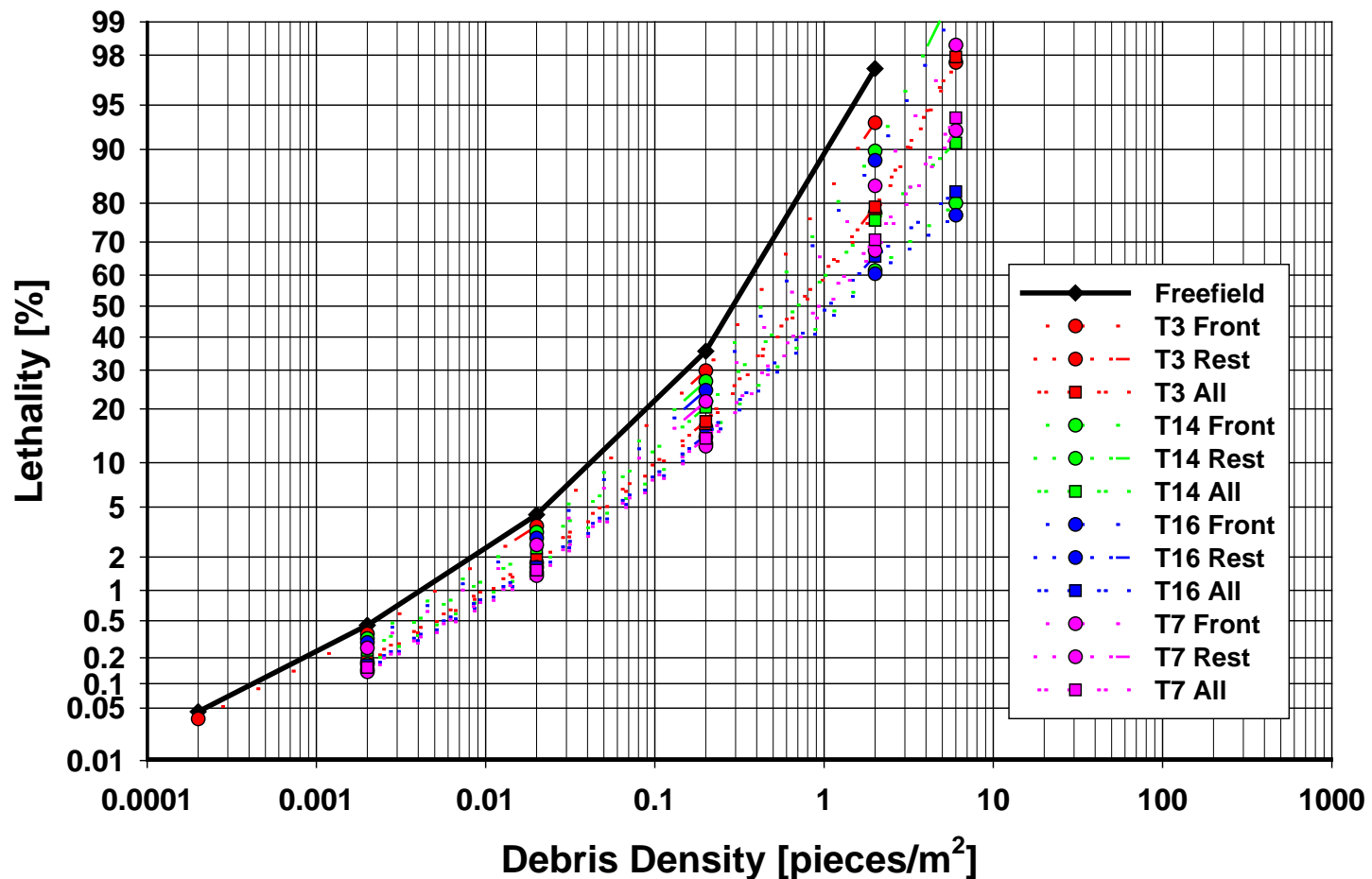

real building → simplified ground plan

For various building sections and various debris number densities average lethalities were calculated with **LambdaT©**
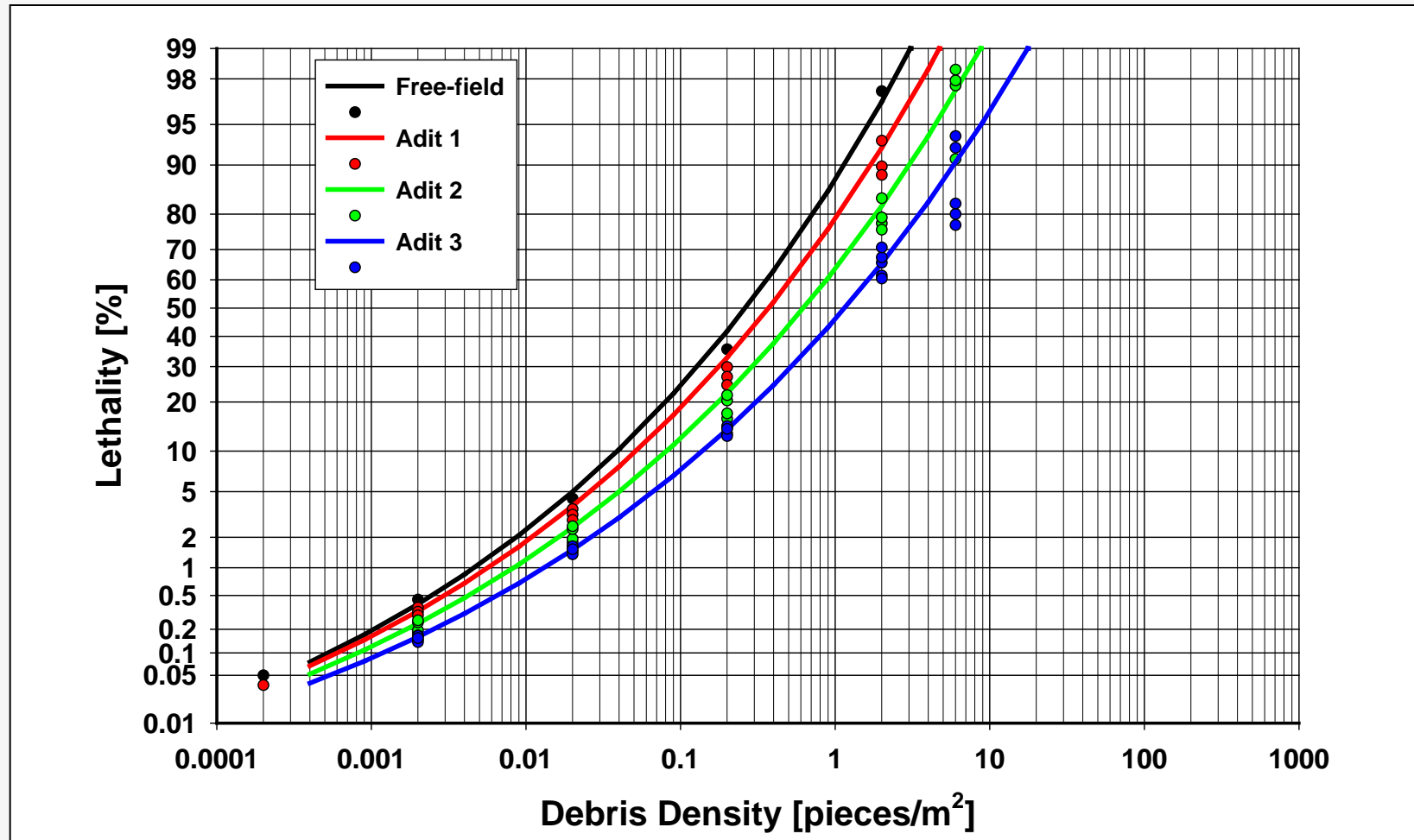
4. Application (3)

- ## Lethality due to Adit Debris from Underground Installations
  - All 4 building types - relevant cross-sections calculated
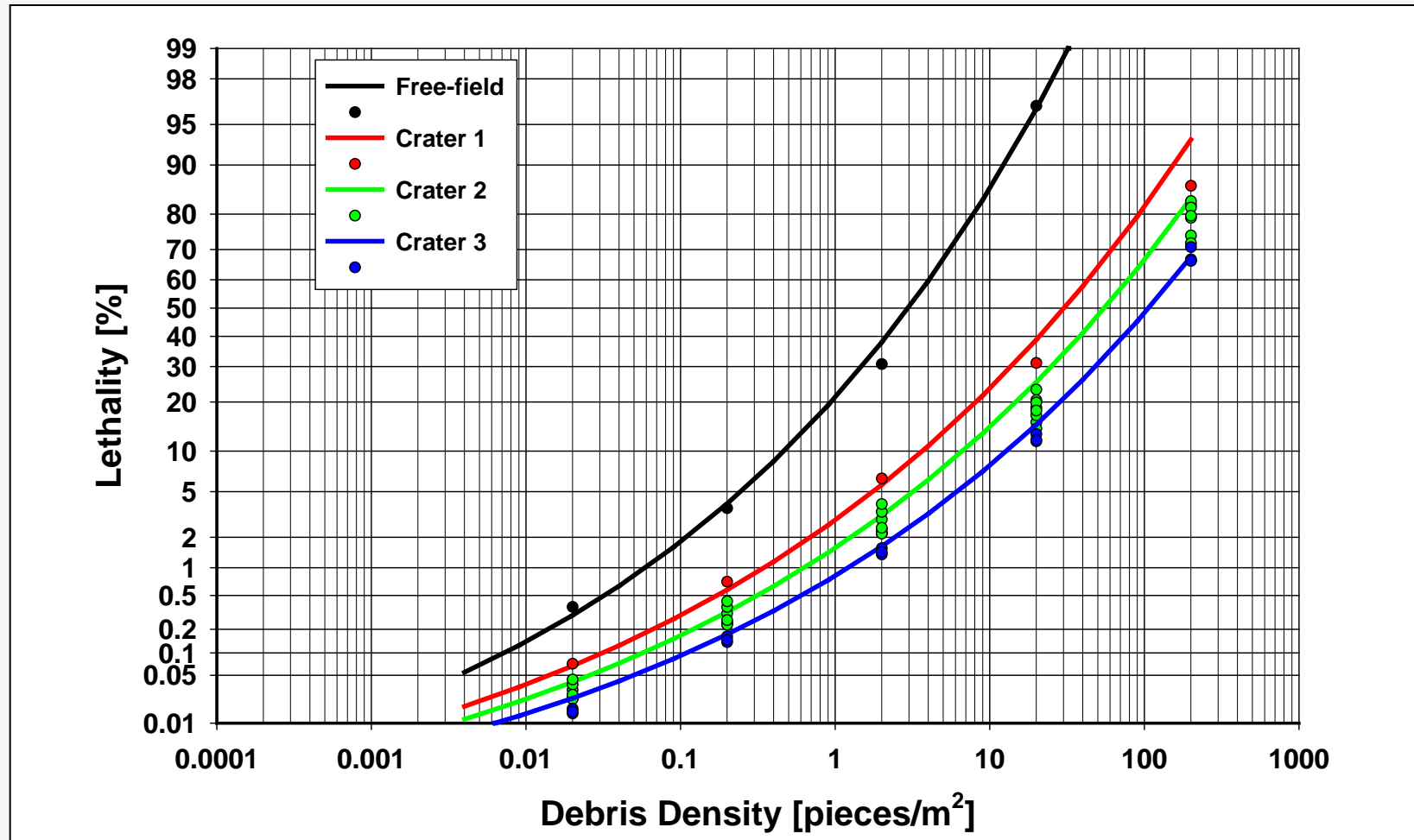
4. Application (4)

- ## Lethality due to Adit Debris from Underground Installations
  - Simplified representative curves

4. Application (5)

• **Lethality due to Crater Debris from Underground Installations**
  - Simplified representative curves

4. Application (6)

- ## Connection Between Building Types and Window Area with Representative Lethality Curves

Building-Type		Windows Area, Orientation	Adit Debris Throw			Crater Debris Throw		
No.	Code		A1	A2	A3	C1	C2	C3
3	EFF-2G	1)		X			X	
		2)	X			X		
		3)		X			X	
7	MFF-3G	1)			X		X	
		2)		X			X	
		3)			X		X	
14	IHF-1G	1)		X				X
		2)	X				X	
		3)			X			X
16	BUF-3G	1)			X			X
		2)	X				X	
		3)			X			X

1)	All facades: window width < 50% of facade width
2)	At least one facade with $\geq$ 50% window width (and h window > 0.5m) and a facade $\geq$ 50% window width facing the PES
3)	At least one facade with $\geq$ 50% window width and a facade < 50% window width facing the PES

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5. Summary

- Procedure and software available to calculate lethality of persons - staying inside buildings or in the open - due to debris throw from explosions

- Any type of buildings may be investigated with LambdaT$^©$

- Debris may originate from explosions in any type of structure or in free-field (building debris, crater debris)

- The explosion may be accidental or terrorist attack related

- Procedure can easily be adjusted, also allowing to calculate lethality due to primary fragments from detonating ammunition

➡ More realistic than applying the 79 J criteria

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